

# Summary of Magnetic Holes Project

August 23, 2005

## 1. Statistical formulation of a scale-free magnetic hole search

Magnetic Holes in the solar wind are anomalous decreases in the interplanetary magnetic field as measured at a particular spacecraft. Such signatures have been observed in durations of several hours all the way down to the time resolution of the fastest magnetometer instruments, and with magnetic field decreases anywhere from a few percent to nearly full annihilation. It has been an objective of this study to implement a general strategy for detecting magnetic holes on all scales at which they can be found. Investigations into the properties of magnetic holes began with collections of events appearing distinct to the “naked eye,” perhaps biased by morphological characteristics or suggestive density and temperature fluctuations. More recent studies have taken the simple approach of cataloging any time period wherein the magnetic field is reduced by more than half.

### 1.1. Parameterization

This investigation takes a statistical approach to the problem of identifying “real” magnetic hole events at all available scales. For eight years of WIND and ACE magnetic field data, the first two statistical moments were calculated at each time point over ranges from three seconds, the spin resolution of the satellites, up to five hours, a bit longer than the longest duration holes observed to date. At any range, when the mean field strength falls below the local mean field by several standard deviations, the measurement is flagged as part of a potential Magnetic Hole. Of course, one must still decide what is meant by “local,” and also decide how deep a decrease must be to qualify.

Our search algorithm is based on two parameters. The parameter  $q_0$  denotes the threshold depth in units of the local standard deviation. The parameter  $s$  specifies the size of the locale around the hole that the field inside it is compared to. For a given window targeting holes of a particular size,  $l$ , the magnetic field inside of the window is compared to the field in a locale of  $s$  windows of the same size before and after the target window. The difference, in units of the standard deviation over that locale, is  $q(t, l; s)$ . If  $q$  is greater than  $q_0$ , a magnetic hole has been found. Some care must be taken to choose  $q_0$  and  $s$  appropriately.

### 1.2. Spectral analysis and establishment of accuracy

Over these timescales, we make use of the observation that, in the turbulent interplanetary solar wind, random fluctuations in density and magnetic field strength exhibit a Kolmogorov-like power law spectrum. By fitting the spectral index of these fluctuations, the turbulent behavior of the solar wind was simulated in order to determine how often our search algorithm ought to be triggered by random fluctuations. Hole occurrence rates were counted for different combinations of  $s$  and  $q_0$  in real and simulated data with a purely turbulent spectrum. The counts converged to a similar value for low  $s$  and  $q_0$ , and both fell to zero as  $s$  or  $q_0$  became large. A locus of relatively

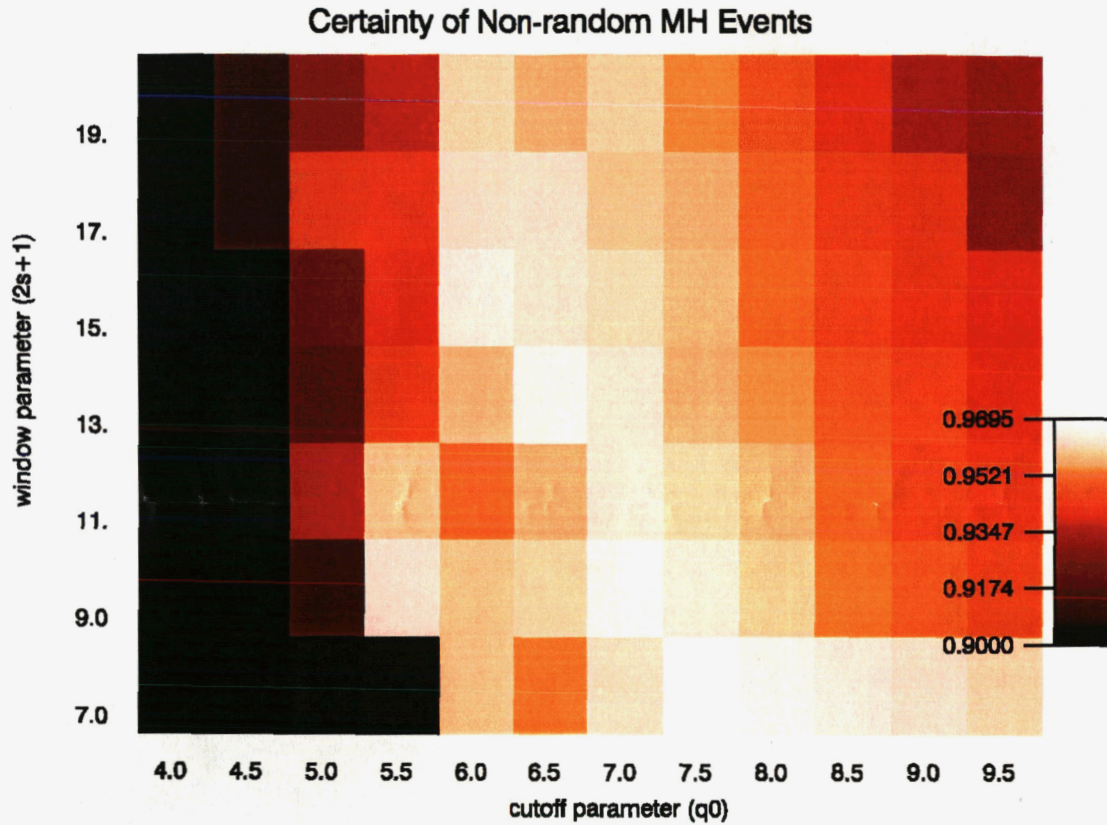


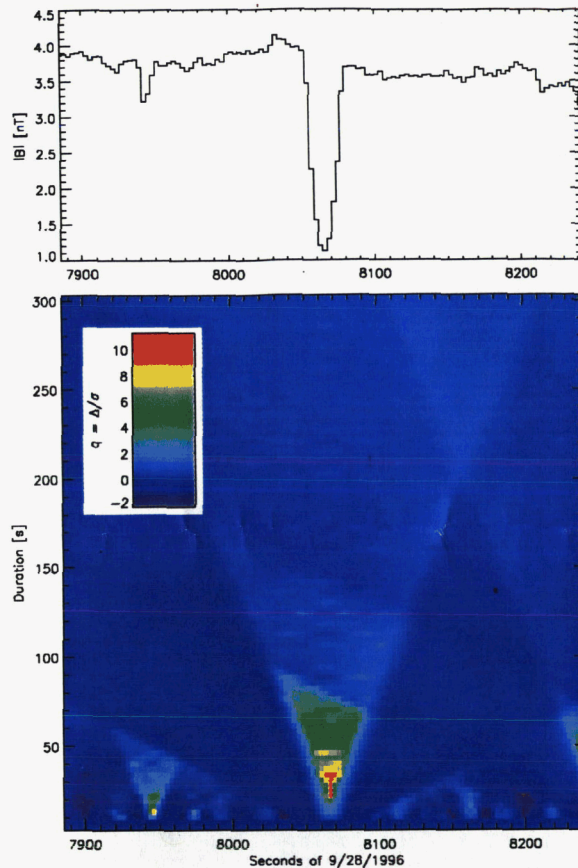
Figure 1: Comparing event counts a real solar wind data stream to those of a simulated, purely turbulent data stream with the same spectral index. Plotted here is the difference between the number of events found in the real and simulated streams, divided by the number found in the real stream.

optimal combinations emerged (figure 1). A choice of  $q_0=7$  and  $s=4$  conveniently provides both 97% certainty and high computational efficiency.

### 1.3. The magnetic hole catalogue

An algorithm was developed to find, group, and catalogue data periods according to the parameter  $q(t, l)$ . An example of a Magnetic Hole signature on this space is shown in figure 2. This algorithm was used to compile a list of magnetic hole candidates for the WIND and ACE spacecrafts over all solar wind transits between 1996 and 2004. Heliospheric current sheet crossings were frequently mistaken for magnetic holes. These were later removed from the catalogue. In all, the final list consists of 2,419 magnetic holes at WIND and 728 magnetic holes at ACE.





**Figure 2: An example of a magnetic hole signature on the parameter space.**

instrument were used to investigate these claims and to more thoroughly survey the plasma properties of magnetic holes. These results will be fully discussed in a paper currently being prepared for submission.

In a “marginally” stable region, the mirror mode parameter,  $R$ , approaches 1. Using WIND 3dp proton moment measurements, we found that while plasma within magnetic holes was, on average, more isotropic than the plasma outside, most magnetic holes do not exhibit strong evidence of the mirror mode instability. We have found that most magnetic holes were not embedded in marginally stable regions. On average, the value of the instability parameter around magnetic holes in this study only slightly exceeded the mean (figure 3). While the elevated perpendicular thermal pressure inside of some holes indicates that some are probably mirror-mode structures, our results indicate that the majority of magnetic holes in the solar wind are not.

Our study has shown that magnetic holes do tend to occur at higher rates with higher plasma beta, and that most are accompanied by an increase in ion density within the hole and an overall increase in thermal pressure. The stability of these pressure-balanced structures was the subject of further examination and will be a matter of continued research.

## 2. High Resolution Plasma Observations

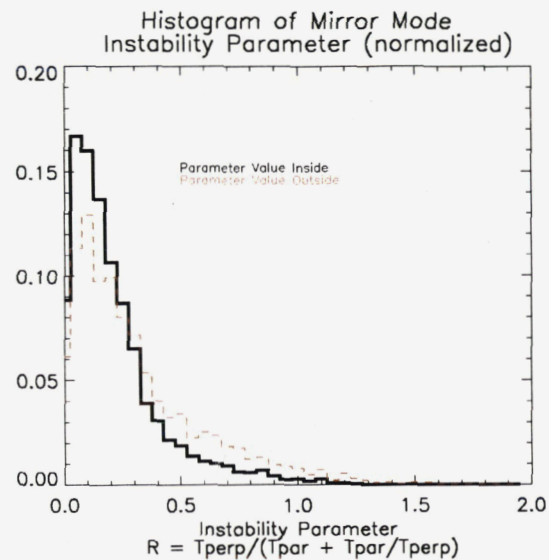
### 2.1 Temperature Anisotropy

One goal of this study has been to test the hypothesis that magnetic holes are either regions of mirror mode instability or the remnants of such regions. In their 1994 and 2000 papers, Winterhalter et al. suggested that the tendencies of magnetic holes to occur at a high plasma beta and to exhibit enhanced temperature isotropy indicate that the mirror mode instability has played a role. Using magnetic field data out of the ecliptic from the Ulysses satellite, they also show that some holes occur in plasma that is only marginally stable to the mirror mode. There was also some evidence of a thermal pressure increase inside some holes, which would be an expected result of any of the anisotropic MHD instabilities.

Plasma measurements from the WIND 3dp and faraday cup plasma instruments, and the ACE SWEPAM

## 2.2. Two-satellite observations

In some cases, the WIND and ACE satellites were positioned such that the same magnetic hole was observed at both spacecraft unambiguously. In these cases, two rather distinct populations were observed. “Kinetic” scale holes, holes that pass the satellite over only a few proton gyroperiods, were seen consistently at the second satellite as though carried by the bulk flow of the solar wind plasma. Holes much larger than this scale, however, were more often seen at the second satellite with a corotation delay. Morphologically speaking, this suggests that large magnetic holes may be elongated along the interplanetary magnetic field. In the extreme case, large magnetic holes may simply be streams of solar origin with low magnetic fields. Kinetic holes, however, clearly convect from the sun with the bulk solar wind (figure 4).



**Figure 3: Histogram showing the stability of magnetic holes to the mirror-mode.**

## 3. Future Work

The stability of magnetic holes and the evolution of the associated plasma parameters will shed further light on their relationship to anisotropic instabilities. The evolution of the anisotropy parameter in and around magnetic holes will indicate whether or not there is an instability at work. Consistency of plasma parameters in large holes from one spacecraft to the other may support the theory that large magnetic holes are simply corotating streams. Presently, a rigorous approach to identifying downstream features with upstream magnetic holes is being explored for kinetic-scale magnetic holes. The evolution of kinetic-scale hole morphology may support or refute the theory that magnetic holes are slow-mode MHD solitons. We also intend to make observations of the wave power spectrum within larger holes in order to address the hypothesis that magnetic holes are phase-steepened Alfvénic structures.

## 4. Posters and Presentations

“Multi-satellite Observations of Magnetic Holes in the Solar Wind,” presentation given at the Fall 2004 meeting of the American Geophysical Union; San Francisco, CA; November, 2004.

“Observations of Kinetic-Scale Magnetic Holes in the Solar Wind,” presentation given at the 35<sup>th</sup> Assembly of the Committee on Space Research; Paris, France; July, 2004.



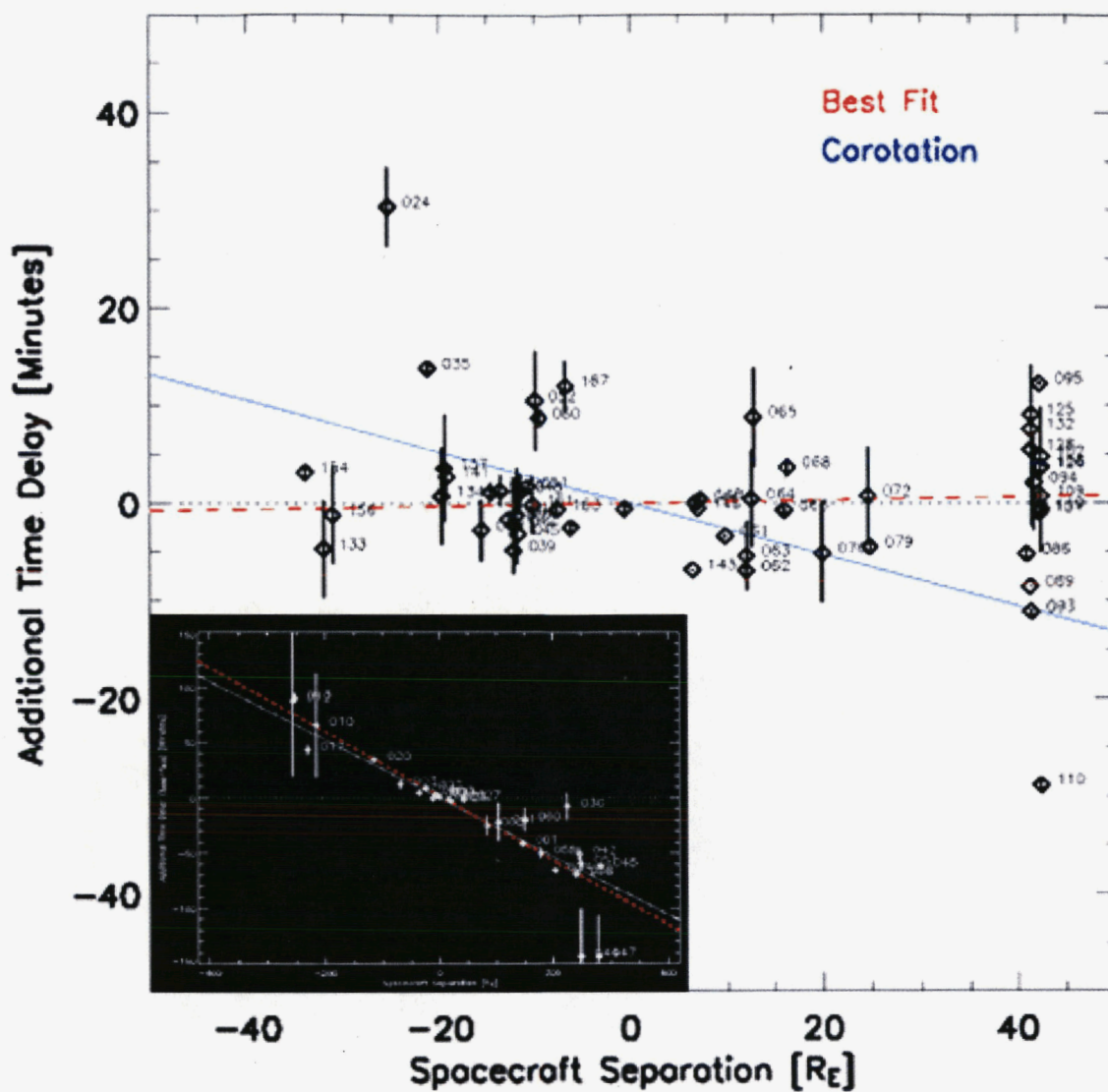


Figure 4: Time Delay, in addition to the bulk flow, for arrival of kinetic-scale magnetic holes at the ACE spacecraft after being seen at WIND. The systematic time delay is nearly zero. In the lower left is a similar plot of large magnetic holes, which does have a systematic time delay corresponding to the corotation time.

“A Scale-Free Search for Magnetic Holes in the Solar Wind,” poster given at the 2004 Solar, Heliospheric, and Interplanetary Environment Workshop; Big Sky, MT; June, 2004.